Modeling of Coastal Ocean Flow Fields

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LONG-TERM GOALS

To understand the dynamics of physical oceanographic circulation processes on continental shelves and slopes with emphasis on the mechanisms involved in across-shelf transport.

OBJECTIVES

To apply numerical circulation models to process studies and to simulations of continental shelf and slope flow fields, including the inner shelf region and the nearshore surf zone, to help achieve understanding of the flow dynamics and, for the surf zone, of sediment transport processes.

APPROACH

Numerical finite-difference models based on the primitive equations are applied to flow problems relevant to the dynamics of continental shelf and slope flow fields and to the circulation in partially enclosed seas. At present, the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987) is being utilized for studies with the primitive equations. The numerical experiments are supplemented with analytical studies whenever possible.

WORK COMPLETED

A modeling study for inner shelf flow fields that examines the wind-forced circulation off Duck, NC in August-November 1994 has been completed as part of PhD thesis research by Brandy Kuebel Cervantes (Kuebel Cervantes et al., 2003a). The model setup assumes alongshore uniform two-dimensional flows with spatial variations in the across-shelf (x) and vertical (z) directions. The model is forced by wind stress and heat flux data collected during the Coastal Ocean Processes (CoOP) field experiments. Both stratified (August) and unstratified (October) conditions exist during the experiment, allowing comparison of the shelf flow response in these two different regimes. In addition to the analysis of model Eulerian velocity, transport, and momentum balance fields, a Lagrangian perspective on fluid motion is central to this study. Lagrangian methods utilized include parcel tracking using a fourth-order Runge-Kutta scheme and a Lagrangian label technique that advects three conservative fields by the model velocities.

Motivated by the complex Lagrangian motion that resulted from the modeling study off Duck, North Carolina, further work with the two-dimensional model has been completed with forcing by periodic

alongshelf winds (Kuebel Cervantes et al., 2003b). A goal of this work is to understand the asymmetries in upwelling and downwelling responses and their implications on the Eulerian and Lagrangian flows. The period and maximum amplitude of the alongshelf wind stress (6 days and 0.1 Nm^{-2}) are typical of August values at Duck. The model is spun up for several forcing periods after which the Eulerian fields are nearly periodic. The Lagrangian techniques of parcel tracking and Lagrangian label advection are utilized to obtain detailed information about fluid parcel motion.

In a separate study by post-doctoral research associate Stephen M. Henderson, a wave-resolving model of water and sediment motion in the benthic boundary layer has been derived. Nonlinear advection of momentum and sediment by waves is simulated in this one-dimensional model by assuming that waves propagate without rapidly changing form. The model has been used to simulate boundary layer flows and sediment transport beneath current meters that were deployed during the Duck94 field experiment (Henderson et al., 2003). Beach erosion and accretion predictions have been compared with observations. Sensitivity of these predictions to the bottom roughness, the bottom boundary condition for sediment pickup, and inclusion or exclusion of nonlinear advection has been tested.

In another effort, numerical model experiments utilizing POM have been conducted to study the mesoscale circulation in the Gulf of California (Martinez and Allen, 2002a,b,c). This is the result of Ph.D. thesis research by Antonio Martinez. The separate effects of forcing by winds and by coastal-trapped waves incident from the south have been examined. A relatively high resolution grid (3 km horizontal grid size, 50 sigma levels in the vertical) has been employed to adequately resolve the mesoscale flow. The wind forcing experiments (Martinez and Allen, 2002a) have been run for 240 days (August 1996 - March 1997). The model results are analyzed for the last 120 day period. The wind stress is obtained from a combined product of scatterometer measurements and NCEP analyses (Milliff et al., 1999). It has been concluded from previous observations (Merrifield and Winant, 1989) that storm-generated incident coastal-trapped waves make a major contribution to mesoscale variability in the gulf. Coastal-trapped wave experiments (Martinez and Allen, 2002b) have been run for an 80 day period 1 July - 19 September 1984 during which time extensive current (Merrifield and Winant, 1989) measurements were made in the gulf. These measurements are utilized for model/data comparisons. In addition, a series of process-oriented experiments have been pursued to better understand coastal-trapped wave propagation in the gulf (Martinez and Allen, 2002c).

RESULTS

Numerical model studies of the two-dimensional circulation off Duck, NC during August-November 1994 provide detailed information about wind-forced continental shelf flow fields. Favorable model/data comparisons of alongshelf velocity and temperature using the CoOP measurements give confidence in model results. The month of August is characterized by a stratified shelf and fluctuating alongshelf wind direction, giving rise to significant across-shelf Ekman transport during both upwelling and downwelling forcing conditions. The August period produces complex Lagrangian behavior due to the switching between upwelling and downwelling winds. In contrast, the shelf during October is weakly stratified and the across-shelf transport is reduced significantly compared to the theoretical Ekman transport for large wind stress values. The October period illustrates a mean downwelling response that advects parcels across and along the shelf and vertically.

Model studies of the shelf flow fields off Duck, NC with periodic alongshelf wind forcing show significant across-shelf, alongshelf, and vertical advection over a period. The mean Lagrangian displacement of parcels on the shelf after one period depends both on their initial location and on the

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initial phase of the forcing. The time evolution of the three Lagrangian label fields, X, Y, and Z, provides an effective way to examine the three-dimensional displacement of fluid parcels on the shelf over a period beginning at $t_i=9.25T$, at which time the wind stress amplitude is maximum upwelling-favorable (Figure 1). Because the forcing is upwelling-favorable in the first quarter-period, the X label shows parcels in the top 10 m move offshore and parcels in the bottom 15 m move onshore. The wind then becomes downwelling-favorable, forcing surface parcels onshore and bottom parcels offshore for the next half-period. In the final quarter-period, upwelling forcing resumes and surface parcels are advected offshore again near their initial positions. The evolution of Z over the same period shows a thin layer of parcels initialized at mid-depth is advected upward toward the coast due to upwelling. After downwelling begins, part of the thin layer remains trapped at the coast because the downwelling response is weak inshore of 5 km. Alongshore advection of parcels, given by the Y label, reaches 40 km to the north and south. At the end of the period, southward displacements exist over a region of relatively large offshore extent from $x=15-35$ km.

Information regarding Lagrangian parcel motion can also be obtained by tracking individual parcels in the traditional manner. Parcel tracking provides direct information that is convenient for constructing a map that may be used to calculate the parcel displacements over large numbers of periods without actually tracking them in the model simulation. The map helps determine the qualitative Lagrangian behavior and provides a clear picture of parcel displacement trends at very little computational cost. The map also makes possible the calculation of approximate values for the largest Lyapunov exponent, which quantifies the complexity of the Largangian motion in a region near the coast and the existence of a clear boundary separating that motion from a region of more regular flow offshore.

The benthic boundary layer model predicted enhanced turbulence in the wave boundary layer, as well as sediment advection by the Stokes drift, boundary layer streaming, and phase shifts between near-bed and free-stream velocities. These processes have been predicted by previously published models, but they have not previously been included together in a single model. We found that simultaneous inclusion of all these processes is important, because they all have a substantial effect on sediment transport (Henderson et al., 2003). The beach erosion and accretion observed during the Duck94 field experiment were predicted with substantial skill (circles, Figure 2). Predictions were not sensitive to bottom roughness, or to the details of the sediment pickup parameterisation. However, predictions were sensitive to the inclusion or exclusion of nonlinear wave-generated advection of momentum and sediment: field-observed shoreward bar migration was not predicted when wave-generated advection was excluded (triangles, right panel of Figure 2). This suggests that advection of sediment by the Stokes drift and by boundary layer streaming flows are important to shoreward sediment transport. Our model had similar skill to the acceleration-based model of Hoefel and Elgar (2003) (crosses, Figure 2), and better skill than the energetics-based model of Bailard (1981) (pluses, Figure 2).

Over the crest of the sandbar, the large sediment fluxes predicted by our model were correlated with the fluxes predicted by the model of Hoefel and Elgar (2003) (Figure 3e). Shoreward fluxes over the bar crest, predicted by our model, were not predicted by the model of Bailard (1981) (Figure 3b). Both onshore and offshore of the bar, there was little correlation between the fluxes predicted by our model and the fluxes predicted by the models of Bailard (1981) and Hoefel and Elgar (2003) (Figure 3a,c,d,f). However the predicted fluxes, both onshore and offshore of the bar, were relatively small.

Model results (Martinez and Allen, 2002a) for the atmospherically-forced mesoscale circulation in the Gulf of California show a complex pattern dominated by the presence of multiple eddies, both cyclonic and anticyclonic, in the southern gulf. The eddies have horizontal scales the order of the gulf width

(≈100 km) and vertical scales of 1000 m. Near the coast along both sides and in most of the north gulf, the circulation is wind-driven and has high variability. Away from the coast in the interior, the velocity fluctuations are characterized by lower variability and are poorly correlated with the wind. The temporal-mean surface circulation consists of southward down-gulf currents along the coast on both sides, with larger magnitude currents on the west side. In the temporal-mean circulation, the cyclonic eddies generally include a northward up-gulf current that is 800 m deep along the east side and a southward down-gulf current with similar depth along the west side. Positive relative vorticity at the surface seems to be produced along the west side and to extend into the interior in the vicinity of cyclonic eddies. Negative vorticity values are significant near anticyclonic eddies and seem to be connected to the east coast.

The evolution of remotely forced coastal-trapped waves in the Gulf of California is studied using numerical experiments with POM (Martinez and Allen, 2002b). Forcing is provided by observed sea level time variability at a remote station south of the gulf that is assumed to propagate northward into the gulf as a mode 1 coastal-trapped wave (CTW). In general, sea level fluctuations are reasonably well represented by the model, with model/data correlations decreasing from 0.76 at Topolobampo, close to the entrance to the gulf, to 0.52 at Santa Rosalia in the central gulf. Model-data correlations of velocity are lower (<0.6). In the gulf, coastal-trapped wave (CTWs) propagate northward along the east side with no significant changes south of the sill, which is 600 km north of the entrance. When incident waves propagating northward in the gulf along the east side arrive at the sill, a small fraction of the wave energy enters the northern gulf and is dissipated. Most of the wave energy is steered at the sill to the west side of the gulf where it propagates southward with decreased sea level amplitude. The weakened waves leave the gulf at the southwest boundary approximately 6-7 days after entering. Some of the incident wave energy is lost into down-slope propagating disturbances generated as the CTWs pass, resulting in relatively intense bottom currents. The contribution of remotely-forced CTWs in the Gulf of California to the total kinetic energy is comparable to that produced by the wind.

The behavior of idealized incident CTW disturbances with different amplitudes and time scales is also examined (Martinez and Allen, 2002c). Incident waves with large, but realistic sea level displacement magnitudes exhibit nonlinear properties. Phase speeds increase as the sea level displacements of the incident waves increase from -30 m to +30 m. Waves of sea level elevation steepen. On the east side, large amplitude elevation waves produce a down-gulf current adjacent to the coast such that the up-gulf currents associated with the waves separate from the coast. The separation process seems to be connected with subsequent down-slope propagation of energy.

IMPACT/APPLICATIONS

The Lagrangian label technique should prove to be extremely useful for general studies of oceanic Lagrangian behavior. The ability of the boundary layer model to predict beach erosion and accretion is noteworthy. This is the first time a physically based model, i.e. a model based on well-established conservation equations, has successfully predicted both shoreward and seaward field-observed sandbar migration. Modeling studies have provided new quantitative information on the nature of the wind- and coastal-trapped wave-driven mesoscale circulation in the Gulf of California.
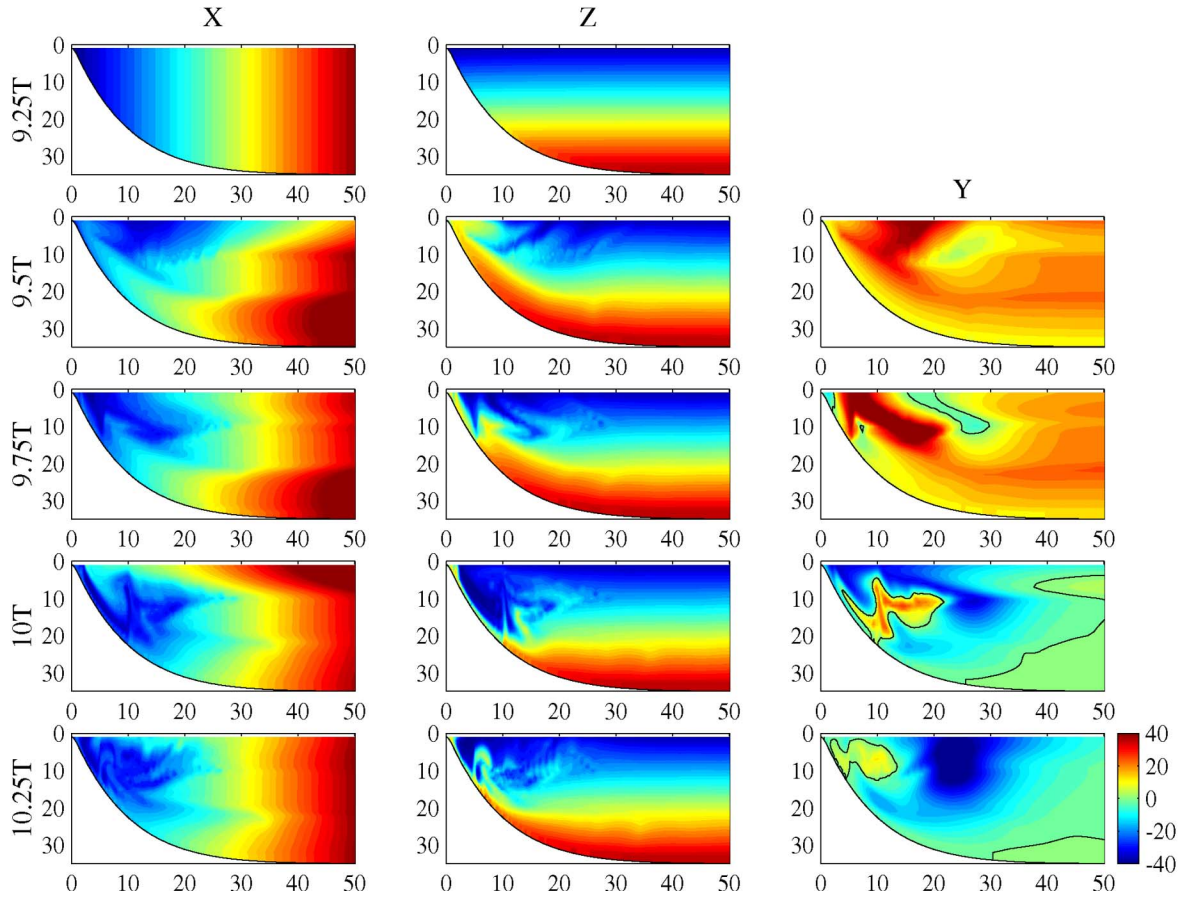
Figure 1. Contours of Lagrangian label fields during one period beginning at t_i=9.25T. The fields are plotted at the initial time and at each subsequent quarter period. The Y label has units of km. The black line marks the 0 contour for Y (Kuebel Cervantes et al., 2003b).
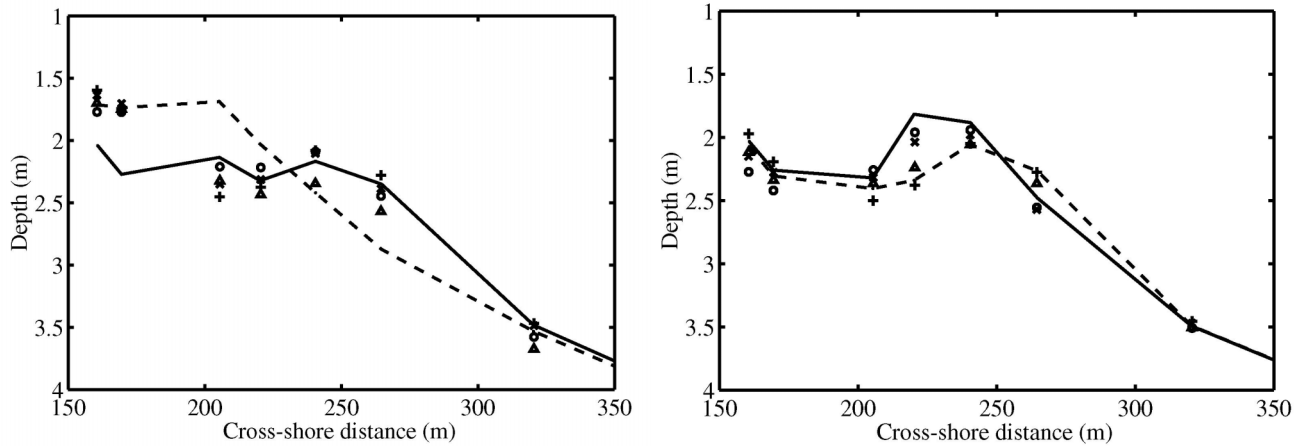

Figure 2. Observed and predicted water depth profiles. Left panel: beach evolution from 1-5 September. Right panel: 22-27 October. Dashed (solid) lines represent observed profiles at start (end) of each interval. Symbols represent predicted profiles at end of each interval. Circles: advective boundary layer model. Triangles: non-advective boundary layer model. Pluses: energetics model. Crosses: combined energetics and acceleration model (Henderson et al., 2003).
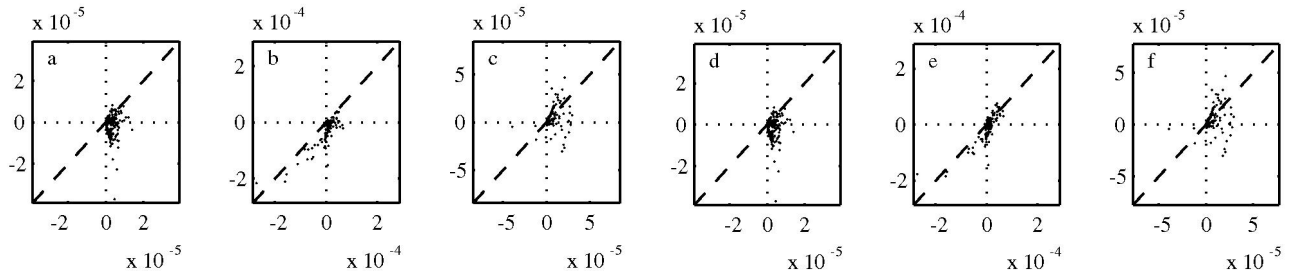
Figure 3. Three-hour averaged depth-integrated shoreward sediment fluxes (m^2s^{-1}) predicted by advective boundary layer model (x axis) versus fluxes predicted by energetics (a,b,c) and acceleration-based (d,e,f) models (Henderson et al., 2003). Predictions are from locations onshore (a,d), over (b,e) and offshore (c,f) of the bar crest.

RELATED PROJECTS

Some aspects of the primitive equation Princeton Ocean Model studies of surf zone flow fields are jointly funded by ONR Grant N00014-99-1-1051, (NOPP) "Development and Verification of a Comprehensive Community Model for Physical Processes in the Nearshore Ocean".

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